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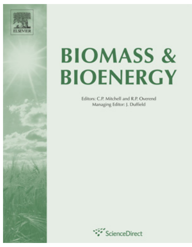

Methanol production via pressurized entrained flow biomass gasification – Techno-economic comparison of integrated vs. stand-alone production

Jim Andersson [a,*], *Joakim Lundgren* [a], *Magnus Marklund* [b]

[a] *Luleå University of Technology, Department of Engineering Sciences and Mathematics, Division of Energy Science, Universitetsområdet Porsön, SE-971 87 Luleå, Sweden*

[b] *Energy Technology Centre in Piteå, Industrigatan 1, SE-941 38 Piteå, Sweden*

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ABSTRACT

The main objective with this work was to investigate techno-economically the opportunity for integrated gasification-based biomass-to-methanol production in an existing chemical pulp and paper mill. Three different system configurations using the pressurized entrained flow biomass gasification (PEBG) technology were studied, one stand-alone plant, one where the bark boiler in the mill was replaced by a PEBG unit and one with a co-integration of a black liquor gasifier operated in parallel with a PEBG unit. The cases were analysed in terms of overall energy efficiency (calculated as electricity-equivalents) and process economics. The economics was assessed under the current as well as possible future energy market conditions. An economic policy support was found to be necessary to make the methanol production competitive under all market scenarios. In a future energy market, integrating a PEBG unit to replace the bark boiler was the most beneficial case from an economic point of view. In this case the methanol production cost was reduced in the range of 11–18 Euro per MWh compared to the stand-alone case. The overall plant efficiency increased approximately 7%-units compared to the original operation of the mill and the non-integrated stand-alone case. In the case with co-integration of the two parallel gasifiers, an equal increase of the system efficiency was achieved, but the economic benefit was not as apparent. Under similar conditions as the current market and when methanol was sold to replace fossil gasoline, co-integration of the two parallel gasifiers was the best alternative based on received IRR.

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1. Introduction

An increased share and a sustainable use of renewable energy are necessary both in the stationary and in the transportation sectors to reduce emissions of greenhouse gases [1,2]. Increasing the efficiency of the vehicle is the most cost-effective way to reduce greenhouse gas emissions in the transportation sector [1], but it is also important to replace fossil automotive fuels with non-fossil alternatives, i.e.

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[*] *Corresponding author*. Tel.: +46 920493916, +46 725210635.
E-mail address: jim.andersson@ltu.se (J. Andersson).

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Nomenclature

Abbreviations

BLG	black liquor gasification
CECPI	chemical engineering's plant cost index
CFB	circulating fluidized bed
EFG	entrained flow gasification
IRR	internal rate of return
MILP	mixed integer linear programming
O&M	operation and maintenance
PEBG	pressurized entrained flow biomass gasification
PI	process integration

biofuels. The latter is particularly important in those countries where internal combustion engines will still be needed due to cold climates [1], e.g. the countries of Scandinavia.

In Sweden, a long term targets have been set to make the Swedish vehicle fleet independent of fossil fuels in the year 2030. In the year 2050, Sweden should not contribute with any net emissions of greenhouse gases to the atmosphere [3]. Currently, Sweden has a general energy tax put on most fuels based on their energy contents. In addition, the country has a carbon tax, which is proportional to the fuel carbon content. In order to promote an increased share of biofuels for transportation, such fuels are subject to a full tax exemption.

In the year 2006, a tax on new motor vehicles was introduced. The tax has one fixed part and one variable based on the specific emissions of CO_2 [4]. From year 2009, the system supports purchases of environment-friendly cars through a tax exemption throughout the first five years after the purchase. This incentive has recently been strengthened with the introduction of an extra subsidy for cars that emits less than 50 g of CO_2 per km. Sweden also requires fuelling stations with an annual selling volume exceeding 1000 m^3 to offer a renewable fuel (e.g. the pump law) [4].

Biomass based methanol is one good alternative to replace fossil petrol in conventional spark engines, only requiring moderate changes in the vehicles and the fuel distribution infrastructure [5]. In 2007, the annual global methanol production rose to 40 million tons [5], where the largest share is used as a feedstock to the chemical industry. Methanol is currently almost exclusively produced via syngas (H_2 and CO) derived from fossil resources, such as natural gas, coal, petroleum oil, naphtha, etc. Production of biomethanol via gasification of lignocellulosic biomass is one alternative that could help decarbonize the transportation sector. Biomass based motor fuels will most likely be produced in existing pulp mills and other large scale forest industries due to the fact that they already have the required biomass handling infrastructure in place [6]. At the pulp mills an important raw material for motor fuel production will be black liquor from pulp production. Previous studies (e.g. Refs. [7–9]) have shown that an investment in black liquor gasification (BLG) is advantageous regarding efficiency and economic performance compared to a new recovery boiler investment for pulp mills. However, the availability of black liquor is limited and it is also strongly connected to the production of pulp and paper limiting the maximum amount of fuel production. Another opportunity, besides black liquor gasification, is direct gasification of forest residues. This alternative is mainly limited by the overall availability of biomass and it can work with low-grade biomass, e.g. logging residues and stumps. This alternative could become particularly attractive if combined with BLG since both upstream (oxygen plant) and downstream process equipment (catalytic conversion into motor fuels) can be co-utilized improving the economies of scale.

A large number of studies exist regarding techno-economic evaluations of motor fuel production systems using biomass based gasification technologies [8,10–18]. Integration of biomass gasifiers in existing industries has been analysed in Refs. [7,8,17,18]. Wetterlund et al. [18], showed important advantages regarding economic performance and energy efficiency when integrating a biomass circulating fluidized bed (CFB) gasifier for production of bio-DME (dimethyl-ether) in a pulp and paper mill compared to a stand-alone production unit. Consonni et al. [7] showed that solid biomass and BLG technologies integrated in a pulp and paper mill for both motor fuel production (DME, Fischer–Tropsch liquids or ethanol-rich mixed-alcohols) and power production would result in good investment opportunities and provide environmental benefits. However, benefits from integrating gasification processes in pulp and paper mills may diminish depending on final products as well as gasification technology [17]. Moreover, integrating a gasification based process in an existing industry may involve an increased operational risk. If for example a BLG plant is deployed, the plant availability must be higher than the host mill to ensure that the spent cooking chemicals (the green liquor) can be recovered, in order to make the overall process efficient and economically feasible.

The entrained flow gasification (EFG) concept is well-known from direct coal gasification and thoroughly presented in the literature, e.g. by Higman et al. [19]. The main advantages of using this concept in coal-based applications are the flexibility in firing a wide variety of coal feedstocks, and the production of a clean, tar-free product gas. However, the main drawbacks (from an energy point of view) are the relatively high oxygen consumption and the need for a finely ground feedstock. EFG reactors usually operate at pressures between 20 and 70 bar and temperatures in the range of 1200–1800 °C, depending on the type of fuel and application. The pressurized entrained flow biomass gasification (PEBG) concept is described in general in Ref. [20] and in more detail in Ref. [21]. In order to obtain an optimal gasification process of the fuel particles, it is important to apply suitable burner design, reactor shape and fuel powder characteristics. The favourable result, which is strived for at these conditions, is a syngas with very low tar content. For synthetic fuel applications (i.e. production of fuels and chemicals from syngas) the requirements on syngas purification are very high. If not, the catalysts used in the synthesis of the fuel product will be deactivated prematurely, which in turn will be costly. Basically, all components other than H_2 and CO need to be removed below ppm levels. The exception is CO_2, which for some reactions is even used at a small concentration like the synthesis for methanol. In some catalytic systems, inerts such as N_2 and CH_4 will accumulate and will therefore have to be removed/limited. Condensable hydrocarbons in the syngas also need to be removed.

Considering operating conditions for synthesis applications, increasing the operating pressure of the gasifier decreases the production costs the most. This is due to the high pressures used in conventional synthesis processes downstream the gasification plant and the energy penalty resulting from the need to raise the syngas pressure. Therefore, the operating pressures are generally in the range 30–80 bar. Furthermore, depending on operating temperature, the introduction of additional steam as gasification agent generally has negative effects on production costs in the considered gasification facility [22]. However, for cases including synthesis gas upgrading and whenever the input fuel has properties enhancing soot formation and resulting in unfavourably low H_2 content (e.g. very low moisture content), addition of steam may still be beneficial overall.

The main aim of this paper was to techno-economically investigate the opportunity to integrate a PEBG process into an existing pulp and paper mill, Billerud Karlsborg in Sweden. The objectives were to find possible and measurable added values with integrated system solutions compared to standalone units. This was done by calculating the biomass to methanol efficiency and the overall system efficiency of the plant for each of the cases (non-integrated and integrated systems). Furthermore, the process economics were evaluated by calculation of the methanol production costs and a cash flow analysis. The analysis was performed for one standalone case and two integrated methanol productions cases, all including a PEBG process for methanol production.

2. Material and method

A process integration (PI) model was used to study integration of biomass based methanol production using the PEBG technology in an existing pulp and paper mill. The modelling was conducted with a bottom-up approach, which allows for a higher detailed level of the modelled sub-processes (i.e. gasification plant) to be integrated with the larger global system (i.e. pulp and paper mill). Each unit in the biomass gasification plant (i.e. from raw biomass pre-treatment to final methanol output) can thereby be represented by an individual submodel and connected via material and energy streams. The whole pulp and paper mill was used as a system boundary to avoid sub-optimization of the energy system.

The gasifier, the gas conditioning and synthesis were modelled in the commercial software Aspen Plus for material and energy balance calculations. The outputs served as inputs for the PI studies, where the pulp and paper mill model based on the reMIND methodology was used. The most important modelling constraint was a maintained pulp production. The PI model was not used for any optimization or minimization. The iterations between the models was done in order to make sure that the steam balance of the mill was kept after replacing the existing boilers with the gasifiers and the downstream gas processing and synthesis. An iterative modelling approach (see Fig. 1) between the two models was therefore adopted to ensure that all constraints of the pulp and paper mill, as well as for the gasification plant, were met. The mass and energy balance results from the Aspen modelling of the stand-alone system were directly used as inputs for the techno-economic evaluation.

This was done in order to assess potential energetic and economic benefits gained by replacing a boiler at the mill with a PEBG unit for methanol production. The economic analysis, see Section 3, was carried out using four different future energy market scenarios and a scenario representing today's market. Due to that the modelling approach was applied on a specific mill, the results cannot be considered as general. However, the modelling approach and the evaluation methods are.

2.1. *The process integration model*

The PI model was based on mathematical programming using mixed integer linear programming (MILP) through the Java-based software tool reMIND [23]. The model structure is composed by a network of nodes and branches, each node contains linear equations to express the materials and energy balances of each steam generating units and steam consumers in the mill. The branches connect the steam generating units and steam consumers in the mill, by representing the internal network of material and energy flows. The network thereby creates an energy system. The model of the existing mill configuration has been validated against operational data. The model development and validation are further described in Ref. [24].

2.2. *Modelling of the biomass gasification system*

To obtain high carbon conversion rates, good syngas quality and steady operation in the reactor, pre-treatment of the incoming biomass is required. The biomass feedstock was dried in an indirectly heated rotary dryer to the desired water content and ground into sufficiently small particles. In the model, the incoming biomass was specified according to the ultimate and proximate analysis. The specific power consumption of the dryer was set at 15 kWh/wet tonne [11]. The incoming biomass was assumed to be dried to a water content of 8 wt%.

The energy consumption for size reducing untreated woody biomass (moisture content up to 13%wt.) has been investigated by Bergman et al. [25]. Based on the LHV, 1–3% of the thermal input was required for power consumption for size reducing to an average particle size between 0.6 and

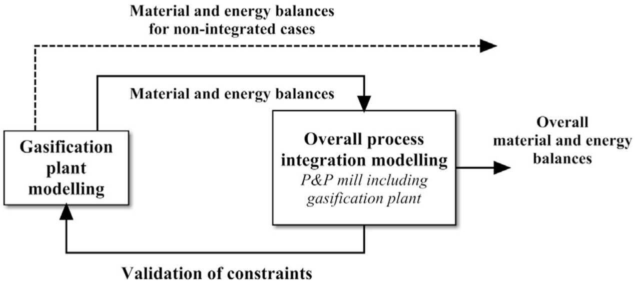

Material and energy balances for non-integrated cases
Material and energy balances
Gasification plant modelling
Overall process integration modelling
P&P mill including gasification plant
Overall material and energy balances
Validation of constraints

Fig. 1 – Workflow approach for the integrated system solutions studies.

0.8 mm. In the modelling, 3% of the thermal input was assumed.

The PEBG was the considered technology for gasification of solid biomass fuels, where the reactor was top-fed with the fuel (wood powder) co-currently with the gasifying agent (pure oxygen). The gasifier unit was modelled in a detailed manner treating the major reaction steps in the gasifier separately (drying, pyrolysis, combustion and gasification). The zones were internally connected by material and heat streams. All zones were represented by conventional Aspen Plus blocks, except for the pyrolysis zone, where an external calculator was included in the model. This approach can increase the dependencies among various parameters and the outcome from the gasifier [26], e.g. the formation of different ash compounds can be connected and linked to the ash content in the incoming biomass.

The temperature of the syngas leaving the reactor was assumed to be 1200 °C after which the gas was partially quenched to 500 °C. The gasification pressure was set at 30 bar(a) in all the modelling cases.

The black liquor gasifier was modelled using the same approach as described for the PEBG and the results were validated against gas composition data presented in Ref. [27]. The largest difference between gasification of solid biomass fuels and BLG was the ash content. Typical black liquor contains 19.4 wt% sodium and 5 wt% sulphur [27]. These two components react together and with other constituents in the black liquor to form NaOH, Na_2S, Na_2CO_3, Na_2SO_4 and H_2S. The sodium compounds were separated from the syngas in the quench as a melt, which was the basis for the green liquor. 36% of the incoming sulphur was assumed to react with hydrogen forming H_2S [28] and will leave the reactor in gas phase.

An air separation unit (ASU) was used to supply pure oxygen to the gasifier(s). The power demand for a cryogenic air separation unit producing oxygen with 99.6 mol% purity consumes 1.0 $MW_e/(kg\text{-}O_2/s)$ [10].

2.3. *Modelling of the gas cleaning, conditioning and methanol synthesis*

For the downstream catalyst, a hydrogen to carbon monoxide ratio slightly above 2 in the syngas favours the methanol generation [17]. The actual H_2:CO ratio of the gas leaving the gasifier was typically around 0.55 [21] and needs therefore to be increased prior to the methanol synthesis. A sulphur tolerant water gas shift (WGS) reactor adjusts the ratio to the desired one by converting CO and steam (30 bar) to H_2 and CO_2.

An acid gas removal (AGR) unit was placed before the synthesis loop, to remove the sulphur contaminations as well as CO_2, NH_3 and HCl. The AGR unit uses cooled methanol to remove separated unwanted impurities and gas species, similar to the Rectisol® process [10]. In the case when the black liquor gasifier operates in parallel to the PEBG, the sulphur content was much higher in the syngas. The sulphur rich stream from the AGR process was then sent to a Claus sulphur recovery unit, where elemental sulphur was recovered [9].

The pressure of the shifted and cleaned syngas was raised to the operating pressure of the catalyst (106 bar with a Δp of 8 bar [13]) by a multistage compressor. The low conversion rate in the catalyst requires recycling of the gas. A fraction (~5%) of the recycled gas was withdrawn in order to prevent accumulation of inert gas in the methanol synthesis loop. These fractions of gases (off-gases) can be combusted in an off-gas boiler for heat production. Before recycling the gas, methanol, water and some carbon dioxide were separated for further purification. More than 98% of the methanol was recovered in the distillation column. The heat needed for distillation was generated by 4 bar steam condensation. Steam was raised in the methanol synthesis both by maintaining a constant exit temperature of 260 °C out from the catalyst and by cooling the outgoing gas prior to the methanol separation.

A simplified description of the complete methanol production process is shown in Fig. 2. The dashed line is valid when a black liquor gasifier is operated in parallel to the PEBG.

3. System description and evaluation

The Billerud Karlsborg AB pulp mill, located in the northern part of Sweden, was used as case basis. This is a partly integrated mill which incorporates batch digestion but was considered be continuous for modelling purpose. The maximum production capacity of the mill is 890 air dried tonnes of Kraft pulp per day and 460 tonnes of paper per day. The mill can principally be divided into two main processes: the fibre line and the chemical recovery process cycle. The fibre processing line includes the pathways for the dissolved cellulosic fibres and extends from the digester (where the pulp cooking occurs) to the pulp bleaching/paper making section of the mill, see Fig. 3.

The integrated chemical recovery cycle is a necessary part of the mill in order to make the overall process economically feasible and environmentally sound. Here, the black liquor, a by-product formed in the pulping process, is an important part that is concentrated in a multi-effect evaporation plant and burned in a so called recovery boiler where combustion of the organic material part provides heat and electricity to the

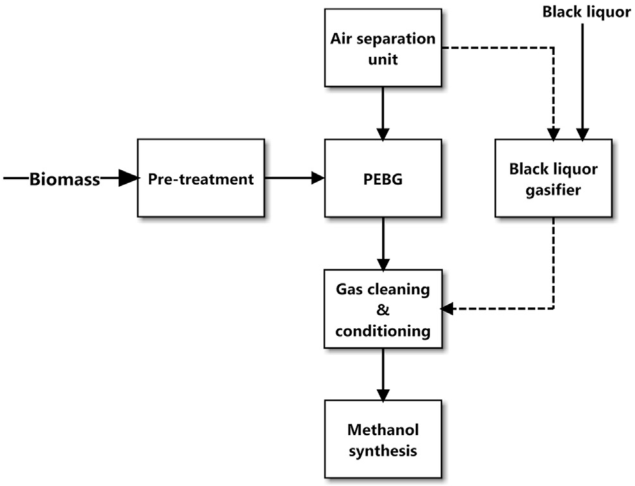


Fig. 2 – Simplified flow sheet for the methanol production plant.

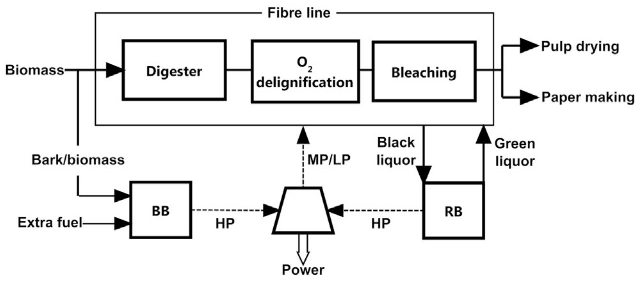


Fig. 3 – Schematic overview of the conventional fibre line and chemical looping at Billerud Karlsborg mill.

Table 1 – Current key energy data of the reference mill (MW).

Electricity produced/purchased	35/16
Steam production for internal consumers	208
Biomass to bark boiler total consumption/purchased	51/7
Oil to recovery boiler	5
Tall oil to lime kiln	17

mill and the inorganic part is partly regenerated to cooking chemicals. The final recovery of these chemicals to NaOH and Na_2S is made in the causticizing plant (i.e. lime kiln). Another (secondary) by-product, extracted from the black liquor evaporators, is rosin soap, which is further processed into tall oil that can be used as an internal fuel in the lime kiln.

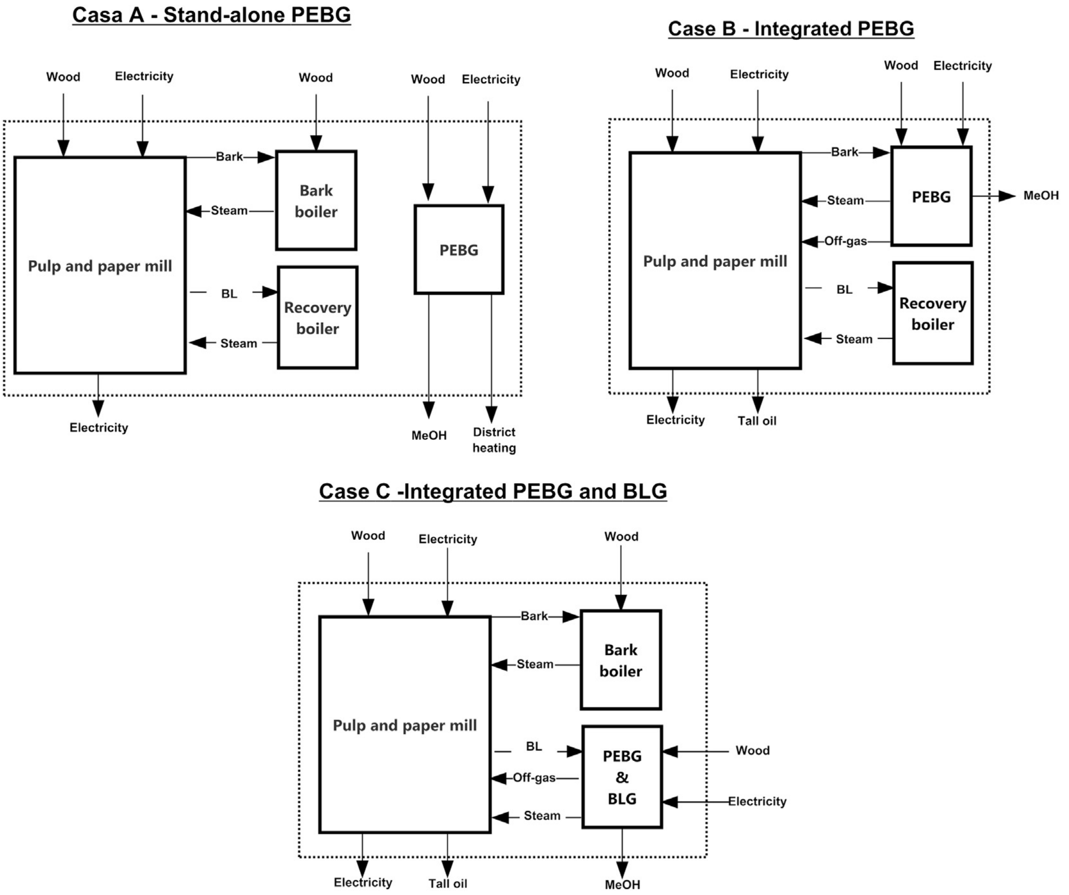
A biomass fired bark boiler is also necessary to produce the marginal demand of process steam. If the supply of internally available biomass is not enough, oil and/or purchased biomass are used (depending on the current fuel market price). The high pressure steam produced in the recovery boiler and the bark boiler is expanded in a steam turbine producing electricity and process steam (10 and 4 bar) for internal use. A small amount of 30 bar steam is also extracted from the turbine for the purpose of soot-blowing in the recovery boiler. Table 1 shows the key energy data of the considered mill, in business-as-usual operation.

3.1. *Case description*

A schematic overview of the three considered cases, a non-integrated stand-alone gasification unit and two integrated gasification systems are shown in Fig. 4. The two integrated cases include the integration of a PEBG in a pulp and paper mill, one with a co-integration of a BLG operated in parallel with the PEBG. In all cases, methanol was the main final product.

3.1.1. *Case A – stand-alone gasifier*

In Case A, the PEBG was operated as a stand-alone gasification plant. To be able to compare the different cases, the size of the stand-alone plant was determined by Case B (see chapter 3.1.2), meaning that the thermal input of the biomass was the same as in that case. The system boundaries in Case A also


Casa A - Stand-alone PEBG

Case B - Integrated PEBG

Case C -Integrated PEBG and BLG

Fig. 4 – Schematic description of the studied cases.

include the original operation of the mill in combination with the stand-alone gasification plant to serve as reference case, as illustrated in Fig. 4. In this case no investments in boilers were considered.

Heat was primarily recovered for steam generation to satisfy the internal demand, with the assumption that the recovered surplus heat could be sold to a local district heating network during the heating season.

3.1.2. *Case B – integrated biomass gasifier for methanol production in a pulp and paper mill*

In this case, the PEBG replaces the bark boiler in the pulp and paper mill. The most important constraint was, as previously mentioned, a maintained pulp production. The gasification plant was therefore dimensioned to deliver the same amount of medium pressure and low pressure steam as the existing bark boiler did. It was furthermore assumed that the steam system of the gasification plant was completely integrated with the steam system of the mill with one common steam turbine. It was also assumed that the bark originally used in the bark boiler could be milled and used as a fuel in the gasifier, with purchased biomass as additional fuel if required. The excess off-gas (tail gas) from the methanol synthesis loop was assumed to replace/reduce the large oil demand in the lime kiln. The surplus tall oil can be sold on the market.

3.1.3. *Case C – integrated biomass gasifier in parallel operation with black liquor gasifier*

In Case C, the recovery boiler was replaced by a black liquor gasifier operating in parallel with the PEBG. The two gasifiers share an air separation unit (ASU), gas cleaning and methanol synthesis as an attempt to reach economy-of-scale effects. Also here, the most important modelling constraint translates to a maintained process steam balance of the mill. Since the black liquor is a by product from the pulp production, the available volume is limited. The size of the PEBG unit was therefore dimensioned to maintain the process steam balance of the mill, when operated in parallel with the black liquor gasifier. The bark boiler was not removed in this case to limit the size of the PEBG unit and the correlated biomass import.

According to Ekbom et al. [9], gasification of black liquor results in a major part of the sulphur content will be converted into H_2S. A weaker green liquor will thereby be produced compared to when the black liquor was combusted in a recovery boiler. In the recovery boiler, the sulphur was recovered as Na_2S and dissolved in water to be hydrolysed to NaHS and NaOH. Ekbom et al. [9], assume that the lower content of NaOH in the green liquor can be compensated by increasing the causticization by 25%, i.e. increasing fuel consumption by 25% in the lime kiln. The excess off-gas from the methanol synthesis loop was assumed to replace/reduce the tall oil demand in the lime kiln. The surplus tall oil can be sold on the market.

3.2. *Overall energy system efficiency*

Two different efficiencies of the gasification plants were calculated; the biomass-to-methanol efficiency and the overall energy system efficiency. The biomass-to-methanol efficiency was calculated as the annual methanol energy output divided by the annual biomass energy use.

For the calculation of overall energy system efficiency, electricity equivalents were used. All energy carriers were converted to their electricity equivalents according to the efficiency of the best-available technologies, see Table 2. The material and energy balance for Cases B–C were calculated on an incremental basis compared to the operation of the pulp mill prior to the integration, i.e. required marginal supply of biomass and other energy carriers needed to produce methanol. This was done to analyse the effects on the overall energy system and determine the best system alternative for producing methanol (i.e. integrated or non-integrated). Case B and Case C were compared to the original operation of the mill and the stand-alone plant (Case A) according to the system boundaries that are defined by the dashed lines in Fig. 4. Biomass used directly for the pulp making and the final pulp products were not included in the calculation of the overall energy system efficiencies.

3.3. *Economic calculations and sensitivity analysis*

In the economic calculations, it was assumed that investment in a new bark and a new recovery boiler was required in Case B and Case C, respectively. The investment cost for a new boiler was converted to an annual capital cost by assuming an economic lifetime of 20 years and an interest rate of 10%, corresponding to an annuity factor of 0.12. Annual operation and maintenance (O&M) cost for the pulp and paper mill was taken from the “Mill stand-alone case” presented in Wetterlund et al. [18]. Costs for wages, insurance for employees and chemical, water and ash disposal were assumed to be included in the annual O&M cost. The investment cost for the bark and the recovery boiler was used for the incremental production cost calculations in Cases B–C, as the difference between the investment in a new boiler and the investment in an integrated gasification plant for methanol production. The capital cost and operating costs for a new boiler were therefore accounted as a reduced cost for the integrated cases. The energy balances for Cases B–C also include any operational changes in the paper and pulp mill caused by the integration of the gasification plant. Investment cost references for the bark boiler and the recovery boiler are presented in Table 3.

The annual O&M cost for Cases A–C was taken from the BIGDME-biorefinery case published in Ref. [18]. It was assumed that the cost can be scaled after the thermal input of biomass and black liquor to the gasifiers for all cases. In Case A, the residual heat was assumed to be sold as district heating

Table 2 – Power generation efficiencies used for calculation of electricity equivalents.

Energy carrier	Power generation efficiency	Comment	Reference
Biomass	46.2%	Biomass integrated gasification combined cycle	[17]
Methanol	55.9%	Gas turbine combined cycle	[17]
Tall oil	55.9%	Assumed the same as methanol	
District heating	10%	Opcon power box	[17]

Table 3 – Reference investment cost in MEuro.

Cost reference	Size unit	Reference size	Cost 2011 (MEuro)	Scale factor[a]	Overall installation factor	Ref.
Recovery boiler	Tons BL/day	3420	136	0.7	1.10	[9]
Bark boiler	MW_{th}	46	24	0.7	1.00	[18]
Pre-treatment	Wet tons/h	34	9	0.79	2.00	[13]
Air separation unit	Tons O_2/day	1001	47	0.85	1.30	[13]
BLG gasification unit and cooling unit	Tons BL/day	3420	92	0.7	1.10	[9]
Biomass gasification unit	kg/h	220	0.3	0.75	1.86	[29]
Gas cleaning unit (prewash, CO-shift, CO_2-sep)	kg/s dry syngas flow	37	38	0.7	1.10	[9]
Claus sulphur plant[b]	Tons BL/day	3420	10	0.7	1.10	[9]
Methanol synthesis unit (incl. compressor & storage)	Tons MeOH/day	1183	65	0.7	1.10	[9]
Off-gas boiler	MW_{th}	355	42	1.0	1.49	[10]
District heating HEX	MW_{th}	355	42	1.0	1.49	[10]
Balance of plant[c]		2% of the total investment cost				[9]
Indirect capital cost[d]		42% of the total investment				

[a] A scale factor of 0.7 was assumed for investments if not specified in the reference.

[b] The same amount of sulphur was assumed to be recovered in the Claus unit per tonne black liquor as in Ref. [9].

[c] Same percentage of the total investment cost, as in Ref. [9] was assumed.

[d] Includes costs for interest during construction (10%), working capital (10%), project administration and development (7%), engineering (5%), start-up cost (5%), royalties, legal permits and insurance (5%).

during 5000 h per year. It should be noted that the sulphur recovered in the Claus recovery unit was neither included in the efficiency calculations nor the methanol production cost estimations.

Price levels and exchange rates for year 2011 (9.03 SEK/EUR and 6.5 SEK/US$) were used for monetary conversions. The annual operation time of the gasifiers and the pulp mill was set at 8000 h. The investment cost was calculated as the sum of the specific investment costs for the major units of the plant (gasifier, WGS, ASU, etc.). The investment costs for each unit were calculated according to the actual capacity, reference size and reference investment cost according to (1):

$$IC = IC_{Ref} \cdot \left(\frac{P}{P_{Ref}}\right)^{n} \cdot F \tag{1}$$

where IC and P denote the investment cost and size, respectively. The subscript (ref) refers to the investment cost and size of the reference plant. *F* is the overall installation factor and *n* denotes the scale factor. The calculated total investment of a plant is generally an uncertain value, and according to Hamelinck et al. [14] the uncertainty may be as much as ±30% of the total investment. The reference investment cost was converted into the price level of 2011, by multiplying the ratio between the Chemical Engineering's Plant Cost Index (CEPCI) of the year 2011 and CEPCI in the year the reference investments were made. Reference size and cost for the major units in the plant are summarized in Table 3.

The economic result is strongly dependent on the price formation on raw materials and future charges for CO_2-emissions. Therefore, the cases were evaluated under four different future energy market scenarios (see Table 4). The energy market scenarios for the year 2030 were developed by Axelsson et al. [30,31], where assessments were made regarding future fossil fuel price level, CO_2 emissions charge and policy support for renewable energy production for an European energy market. The biomass price was set according the high-volume users' willingness to pay for biomass, which in these scenarios was coal power plant co-firing biomass [18]. Consequently, coal and CO_2 charges determine the price for biomass. In scenario 1, the methanol price was set to the current selling price level (January, 2012) [32]. For each future scenario, the methanol prices were scaled in the same way as DME was scaled in Wetterlund et al. [18], where the price for biofuel was set after the fossil fuel price so that the pump cost was the equivalent on energy basis. A biofuel policy support was implemented via assuming that stand-alone large-scale biofuel production plants have equal willingness to pay for biomass as a coal power plant, e.g. here the methanol produced via biomass gasification.

Table 4 – Energy market scenarios [30,31].

Scenario		1	2	3	4	Today scenario
Fossil fuel price level		Low	Low	High	High	
CO_2 charge		Low	High	Low	High	
Prices and policy instruments						
Wood fuel	EUR/MWh	32	58	35	61	22
Electricity	EUR/MWh	69	92	75	100	66
Heavy fuel oil (incl. CO_2 charge)	EUR/MWh	46	68	68	91	46
Tall oil (selling price)	EUR/MWh	35	35	58	58	35
Methanol (selling price)[a]	EUR/MWh	59	79	91	113	184
CO_2 charge	EUR/tCO_2	36	111	36	111	36
Renewable electricity policy support	EUR/MWh	26	26	26	26	6.9
Biofuel policy support	EUR/MWh	47	68	20	42	0
District heating	EUR/MWh	19	50	27	57	50

[a] In the today scenario, the methanol selling price was converted from the current selling price 1.67 *Euro/litre* of fossil gasoline. The fossil gasoline price includes production, distribution, energy tax, CO_2-tax and VAT.

Biomass is often associated with one of the largest annual costs and a low biomass price (compared to the biomass prices in the future scenarios) can therefore create more favourable conditions for methanol production. As a complement to the future market scenarios the economic feasibility of the cases was also analysed in a "today scenario" (see Table 4), where methanol was sold to replace fossil gasoline with an estimated distribution cost of 0.222 Euro/litre per gasoline equivalent. In the today scenario, methanol was fully exempted from taxes in an approach to mimic the current Swedish biofuel policy support. The biomass price, electricity price, the renewable electricity support as well as the district heating selling price was based on the Swedish energy market [33–35], while the other parameters were assumed to be the same as in scenario 1.

If the income from the biofuel policy support in the future energy market scenarios was added to the methanol selling price (i.e. included as revenue in the production cost calculation) the revenues from each unit of methanol sold increase by 22–86% depending on scenario. The total revenues for production of a renewable motor fuel (here methanol) are therefore very influenced by the level of biofuel policy support for the future energy market scenarios. The biofuels policy support in these future energy market scenarios should be viewed as an incentive to initially aid biofuels to become competitive to fossil fuels. However, after a biofuel market is developed and commercialized, the policy support is supposed to gradually be phased out. Thus, biofuels should in the end be able to compete without any support. The production cost was therefore calculated including the given support according to each scenario as well as without any support at all.

The different energy market scenarios and the annual capital cost were used to calculate the production cost for Cases A–C and compare the potential economic marginal against the methanol selling price. Cases with net positive economic marginal were also evaluated in a cash flow analysis to determine the internal rate of return (IRR). In the IRR analysis, the production was assumed to be at 25% of the full capacity during the first year and increase with 25%-units annually until the start-up period ends. The investment cost was assumed to be paid during a three year construction period.

A sensitivity analysis was carried out, where identified parameters with potentially high influence on the methanol production cost were investigated. The studied parameters are:

- **Surplus tall oil sales**. Not all off-gas may be suitable for utilization in the lime kiln and the possibility that exist no surplus tall oil will be available for market sales. Therefore, the economic influence on the sale of surplus tall oil was investigated.
- The **capital cost** is a critical and uncertain parameter for the process economics. In the analysis the annual capital cost was assumed to change ±30%. This can be viewed as a fluctuation in the capital investment cost but also as a changed return on equity, i.e. a varied annuity factor that consequently translate to a changed interest rate and/or assumed economic lifetime.
- The influence of the **O&M cost** was studied by varying it in the range of ±30%.
- Three operational plant parameters were investigated with potentially vital influence on the process economics. The influences of a separate change in **methanol production** by ±10%, **electricity consumption in the gasification plant** by ±30% or **annual operation time** ±8%, were analysed.

A price change for an individual commodity was not investigated because the used scenarios were designed by interdependent parameters.

4. Results and discussion

Three different system configurations using PEBG technology to produce methanol were studied, one stand-alone plant (Case A) and two integrated into a pulp and paper mill (Cases B–C). The resulting material and energy flows for the cases are presented in Fig. 5. A biomass-to-methanol efficiency was calculated at 55% in Cases A and B, while Case C shows a slightly lower efficiency, 53%. The overall energy system efficiency (calculated as electricity-equivalents) of the studied cases was estimated by the incoming and outgoing energy flows over the systems' boundaries represented by dashed boxes in Fig. 5. The results show that the system configurations according to the original operation of the mill and the non-integrated Case A reached an overall system efficiency of 50%. By integrating a PEBG unit and replacing the bark boiler (Case B), the overall system efficiency increases to 57%. With the integrated gasifier capacities chosen in this study, the net steam production supplied to the mill was more or less only sufficient to cover the steam demand of the different subprocesses of the mill. In the case where the PEBG unit was operated in parallel with BLG (Case C), hardly any high pressure steam was expanded in the steam turbine. The electricity production would therefore decrease from 35 MW (Case A) to only 4 MW for Case C. Such a significant change in operating conditions would probably require a new steam turbine. An investment in a new turbine was not considered in the current analysis and Case C was thereby noted for a zero electricity production. However, by removing the recovery boiler in favour of integrating PEBG in parallel operation with BLG (Case C) the overall system efficiency also increased to 57%.

Table 5 shows the resulting overall energy and material balances of the different cases. The energy balances for Cases B and C also include required operational changes in the pulp and paper mill due to the integration of the gasification plant. Table 5 also shows the specific investment cost of the major units as well as the O&M costs for each case. In all cases, the investment costs for pre-treatment, air separation unit and gasifier(s) represent the major part of the investment cost for equipment (56–66%). Case C showed the lowest specific investment of approximately 1.6 MEuro/MWh methanol produced. In Cases A and B, the specific investments were around 2.0 MEuro/MWh of methanol and 1.8 MEuro/MWh of methanol produced, respectively. At the pulp and paper mill necessary biomass handling infrastructure is in place, which may reduce the investment cost for an integrated methanol production plant. This was especially true for Case B, where the capacity of the plant (338 MW_{th}) should not impose very large changes for the incoming biomass handling

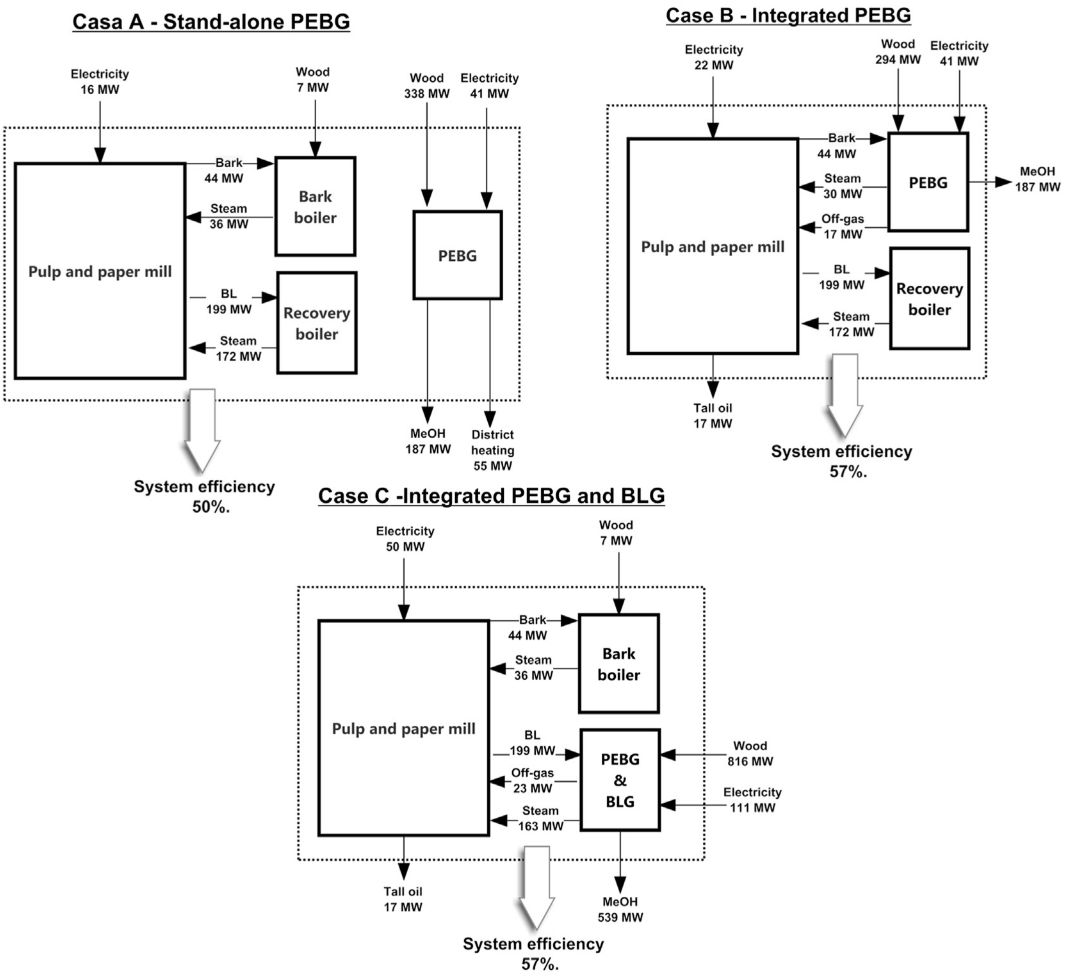


Fig. 5 – Incoming/outgoing energy and material flows for the different cases. The dashed boxes represent the system boundaries used for the overall energy efficiency calculations.

infrastructure. These benefits were not addressed in the economic evaluation.

The resulting production cost for Cases A–C depended on the energy market scenarios 1–4 as well as the today scenario is presented in Fig. 6. The methanol production cost includes costs and revenues from other products (electricity, heat, tall oil, etc.), and the annual capital cost. In Fig. 6, the methanol production cost is also presented when the biofuel policy support also was included as revenue.

In the today scenario a biofuel policy support was implemented via tax exempting renewable motor fuel production (here methanol), because the methanol was assumed to replace fossil gasoline. All cases showed a considerably lower production cost compared to selling price in the today scenario and thereby an opportunity for a good production profitability. Note that the production costs in the today scenario also include a distribution cost of 0.222 Euro/litre. Nevertheless, if the methanol export was not tax exempted, the production costs were unable to compete with fossil gasoline (not presented in Fig. 6).

The importance of a biofuel support was also evident when the gasification systems were evaluated in the four future energy market scenarios, where none of the system configurations could be competitive with the methanol selling price without the support, see Fig. 6. At a low fossil fuel price level and high CO_2 charge (scenario 2) the biofuel policy support was the highest (68 Euro/MWh), but the economic benefits gained via integration cannot reduce the production cost to compete with the methanol selling price. Note that this biofuel policy support level roughly correlates to the tax exemption benefits methanol receives in the today scenario.

For all the other considered scenarios, more favourable economic benefits with integration compared to stand-alone operation were obtained when the biofuel support was included. In scenario 3, the fossil price was high but the CO_2 charge was low, which makes the biomass price relatively cheap and compared to the production cost of methanol Case B showed the largest economic net marginal in this scenario, see Fig. 6. Case C showed breakeven production cost compared to the methanol selling price in the scenarios where the CO_2 charges were low (scenarios 1 and 3), because of the relative low biomass prices. In the scenarios with relative high biomass prices (scenarios 2 and 4), high import of biomass will be penalized and this explains the negative marginal's received for Case C in these scenarios. Overall, the effect of the zero net electricity production in Case C was also a main

Table 5 – Overall annual energy and material balances and capital investment costs.

Plant production	Comment	Unit	Ref P&P[a]	Case A	Case B	Case C
Consumables						
Biomass input capacity/black liquor	As received, 40% moisture	MW	51[b]	338	338	816 (199)[c]
Biomass, annual input	As received, 40% moisture	tonnes	121 864	840,622	840,622	2,029,430
Power consumed		MW	50	41	91	161
Ash disposal	2% of dry biomass	tonnes/year		12,609	12,609	30,441
Oil		MW	5			
Products						
Methanol		MW		187	187	539
Methanol, annual output		tonnes		270,080	270,080	779,713
Tall oil		MW			17	17[d]
Tall oil, annual output		GWh/year			136	136
Power produced		MW	35		29	0[e]
Heat/steam produced		MW	208	55	30	135
Heat, annual output (during 5000 h annually)		GWh/year		275		
Capital investment cost		Unit				
Pre-treatment		MEURO		37	37	99
Air separation unit		MEURO		43	43	109
BLG gasification unit and cooling unit		MEuro				72
Biomass gasification unit and cooling unit[f]		MEuro		65	65	127
Gas cleaning unit (pre-wash, CO-shift, CO_2-sep)		MEuro		33	33	70
Sulphur handling (Claus plant)		MEuro				7
Methanol synthesis unit (incl. compressor & storage)		MEuro		57	57	119
Off-gas boiler		MEuro		10		
District heating HEX		MEuro		10		
Balance of the plant		MEuro		5	5	12
Recovery boiler		MEuro	106			
Bark boiler		MEuro	24			
Equipment and assembly		MEuro	24/106	260	240	615
Indirect cost (42% of equipment and assembly)		MEuro	10/44	109	101	258
Total investment cost		MEuro	35/150	369	341	874
O&M[g]		MEuro/year	2[i]	27	24	82
Capital costs[h]		MEuro/year	4/18[i]	44	40	103

[a] Refers to business-as-usual operation of the pulp and paper mill. All residual heat was used internally.

[b] Total biomass use in the bark boiler.

[c] In Case C, 51 MW of biomass was supplied to the bark boiler. The total biomass use was 864 MW (PEBG and bark boiler) plus 199 MW of black liquor in the BLG.

[d] In Case C, the lime kiln fuel demand was assumed to increase by 25%. To satisfy the increased demand, 22 MW off-gases must be supplied from the gasification plant. 17 MW of surplus tall oil will be available for market sales.

[e] A significant decrease in internal electricity production occurs with the assumed gasifier capacities. Neither the electricity production nor an investment for a new turbine was included.

[f] Investment was valid for 4 parallel biomass gasifier units, each with a third of the needed capacity, for enable maintenance of one unit while operating at full capacity in the other three units.

[g] Costs for wages, insurance for employees and chemical, water and ash disposal.

[h] An annuity factor of 0.12, corresponding to an economic lifetime of 20 years and a 10% interest rate, was used.

[i] The capital cost and O&M cost for a new boiler were accounted as a reduced cost for the integrated cases in the economic evaluation.

explanation in these economic results together with the low biomass-to-methanol efficiency. This points out that the full integration case configuration (Case C) was far from optimal from an economic point of view and an adjusted configuration would most probably end up in more favourable economic results. The stand-alone unit (Case A) showed a negative marginal in each scenario.

The result of the cash flow analysis is presented in Fig. 7 for cases with a net positive economic marginal (see Fig. 6). As illustrated in Fig. 7, an IRR below 10% was achieved in Case B, at three of the future energy market scenarios. At current conditions, the economy-of-scale effects were apparent and the parallel operation of a biomass and black liquor gasifier (Case C) seems to be the most attractive alternative when considering the IRR. Still, Cases A and B showed attractive production profitability.

Fig. 8 shows the methanol production cost as a result of the sensitivity analysis. The costs and revenues of other products (electricity, heat, tall oil, etc.), were also here included in the production cost calculation. The methanol yield has a large influence on the production cost. A 10% change in the yield results in a production cost increase/decrease by 9–11% in all scenarios. Slightly smaller influences were observed for the production cost when the O&M cost changes within the same range. A large uncertainty is the investment costs. An investment cost change of 30% results in a methanol production cost change in the range of 4–8%, depending on case and scenario. The production cost can therefore be viewed as relatively insensitive to large capital cost fluctuation. This was particularly evident for Case C (see Fig. 8) due to the low specific investment cost. If no tall oil was liberated and sold (i.e. the off-gases not used to replace the tall oil in the lime

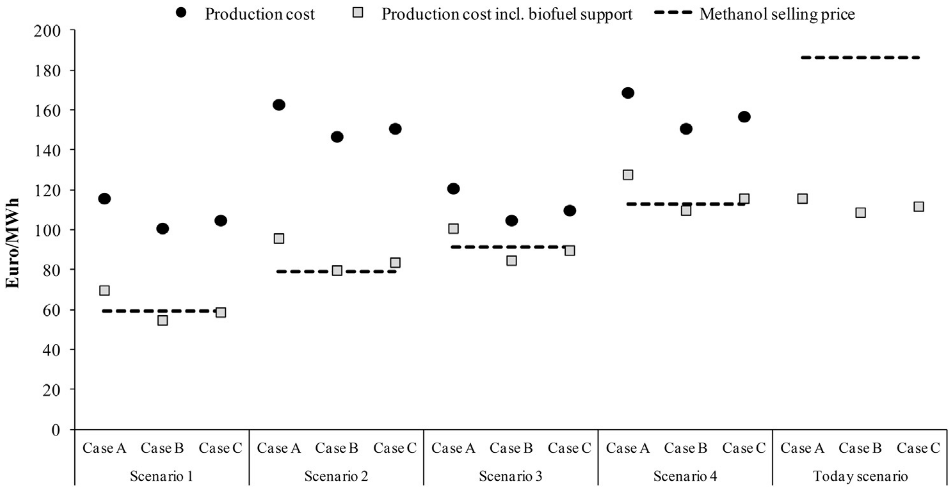


Fig. 6 – Methanol production costs for Cases A–C during the different market scenarios.

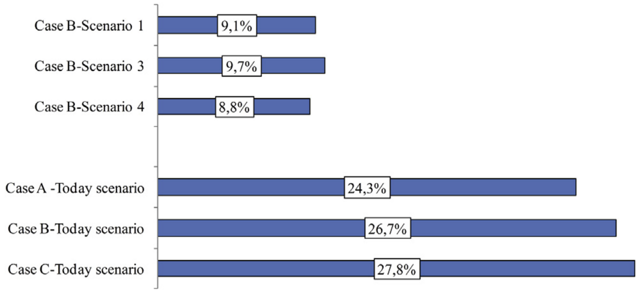


Fig. 7 – IRR for the different cases when the biofuel policy support was included.

kiln) the changes were small in Case C. The methanol production cost in Case B increased more than in Case C, with the highest production cost increase noticed in scenario 3 (when no surplus tall oil was available for sale).

None of the assumed plant improvements in Fig. 8 (increased methanol production, decreased O&M or investments cost, etc.) can by themselves lower the production cost to the same degree as the biofuel policy support did (Fig. 6). Thus, it is obvious that initial economic policy support will be required to make methanol production via PEBG economically feasible.

5. Conclusions

The main aim of this study was to perform a techno-economic evaluation of methanol production via the PEBG process integrated into an existing pulp and paper mill. Three different system configurations using PEBG technology were studied, one stand-alone plant (Case A) and two integrated into a pulp and paper mill (Cases B–C).

Replacing the bark boiler in a pulp and paper mill in favour of PEBG for methanol production (Case B) increases the overall plant efficiency by 7%-units (calculated as electrical equivalents) compared to the original operation of the mill operating together with the non-integrated PEBG concept (Case A). However, substantial increases in the imports of biomass feedstock and electricity were needed in order to fulfil the steam demand of the mill. Methanol produced via parallel operation of a solid biomass gasifier and a black liquor gasifier, Case C, received the same overall plant efficiency as Case B (57%). The positive effects from the high internal use of

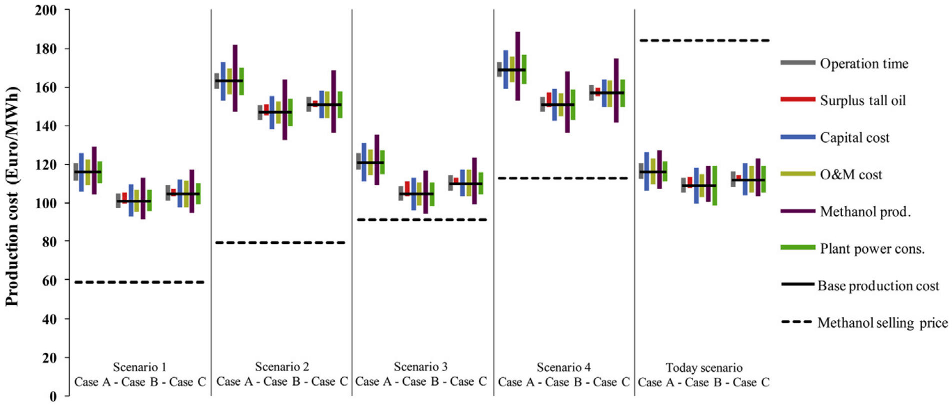


Fig. 8 – Results of the sensitivity analysis for Cases A–C.

resources (black liquor and biomass) in this case therefore compensate for the zero electricity production. However, the effect of the zero net electricity production in Case C becomes evident in the economic results and was one of the main reasons why Case C consistently has a higher methanol production cost then Case B in all scenarios. For all the cases, it was obvious that a biofuel policy support was needed in order to make production of biomethanol economically competitive for the considered process concepts. In comparison to the stand-alone plant (Case A) the methanol production cost was lowered in the range of 11–18 Euro/MWh for the integrated Case B and Case C.

Under similar conditions as today, attractive investment opportunities were shown for all cases if the methanol was exempted from taxes and sold to replace fossil gasoline. The economics-of-scale was apparent and the parallel operation of a biomass and a black liquor gasifier (Case C) seems to be the most attractive alternative when considering the internal rate of return.

The production profitability of methanol production via biomass gasification was however diminished when evaluated under future energy market scenarios, where price assessments were made based on the fossil fuel price level, CO_2 emissions charge and biofuel policy support for a European energy market. The relative high biomass prices in a future market penalized the viability of Case C due to its high biomass import demand. The positive economy-of-scale effects cannot compensate for the relative high operational costs and the smaller integrated route with a PEBG unit (Case B) was therefore here a better investment opportunity.

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